PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

Astronomical search for origins: Are we alone?

James B. Breckinridge

James B. Breckinridge, "Astronomical search for origins: Are we alone?," Proc. SPIE 5166, UV/Optical/IR Space Telescopes: Innovative Technologies and Concepts, (30 January 2004); doi: 10.1117/12.507763

Event: Optical Science and Technology, SPIE's 48th Annual Meeting, 2003, San Diego, California, United States

Astronomical Search for Origins: Are We Alone?

James B. Breckinridge
Origins Technologist
Jet Propulsion Laboratory, California Institute of Technology,
4800 Oak Grove Drive, Pasadena, CA, USA 91109-8099

ABSTRACT

Recent advances in astronomical research have led to a much-improved understanding of the evolution of the physical Universe. Recent advances in biology and genetics have led to a much-improved understanding of our biological Universe. Scientists now believe that we have the research tools to begin to answer one of man's two most compelling research questions: Are we alone? and How did we get here? This paper reviews the requirements and challenges we face to engineer and build the large space-based systems of interferometers and innovative single-aperture telescopes to detect and characterize in detail earth type planets around stars other than our sun.

1. INTRODUCTION

Since the beginning of time, when man first looked to the stars above he has asked the questions: Where did we come from? Are we alone? Now for the first time we are making a major systematic effort driven by scientific enquiry to directly investigate these two profound questions. The scope of the NASA Origins Program[1] coordinates the development of giant optical and infrared space telescopes, astrobiology, interferometers for space imaging, and ultra-precise astrometry, with fundamental research in physics, astronomy, biology, and chemistry to open new windows for science and technology.

Some of the tools for this research are The Keck Interferometer, The SOFIA airborne infrared telescope system, the Hubble Space Telescope (HST), the Space Infrared Telescope Facility (SIRTF)[2], and the new exciting James Webb Space Telescope (JWST)[3]. In addition, an aggressive new technology program under the name Terrestrial Planet Finder (TPF)[4] is pursuing technology that will enable the **discovery** and some characterization of terrestrial planets outside our solar system.

In the future technology programs just starting up will enable the detailed characterization of planets around stars other than our own and, some day will record an image with spectral data of an Earth-like exoplanet.

2. SCIENCE

The origins program will answer critical science questions in four areas.

1. Emergence of the Modern Universe
    a. How did the cosmic web of matter organize into the first stars and planets?
    b. How do different galactic ecosystems (of stars and gas) form and evolve planets and living organisms?
2. Stars and Planets
    a. How do gas and dust become stars and planets?
    b. Are there planetary systems around other stars and how do their architectures and evolution compare with our own solar system?
3. Habitable Planets and Life
    a. What are the properties of giant planets orbiting other stars?
    b. How common are terrestrial planets? What are their properties? Which of them might be habitable?
4. Is there life on planets outside the solar system?

UV/Optical/IR Space Telescopes: Innovative Technologies and Concepts, edited by Howard A. MacEwen, Proceedings of SPIE Vol. 5166 (SPIE, Bellingham, WA, 2004) · 0277-786X/04/$15 · doi: 10.1117/12.507763

3. SYSTEM VISIONS FOCUS COHERENT TECHNOLOGY PROGRAMS

The process NASA uses to focus a technology program is to create a detailed system vision or model of the space astrophysics sensor system required to make a scientific measurement of critical importance. Several mission visions have been recently[5] identified whose successful completion will greatly expand our understanding of the science questions within the Origins program. In addition, technology development is also in process for several other missions within the Origins mission portfolio. These mission studies, visions, and pre-phase A studies include the following mission visions

3.1 Terrestrial Planet Finder

The TPF pre-phase A project currently supports three mission visions:

1. A large aperture optical/infrared coronagraph for direct detection of terrestrial planets shining in reflected starlight within 3 arcsec of the bright parent star of brightness 10^9 times brighter than the planet.
2. A structurally connected optical/infrared interferometer of 25-to-50-m separation.
3. A free-flying optical/infrared interferometer of very high resolution.

It is the goal of the terrestrial planet finder project to find terrestrial planets outside the solar system and to characterize them as best as possible within the resources of the project. Follow-on detailed study by the life-finder mission discussed below, may reveal the presence of another planet outside the solar system with life on it.

3.2 Far-Infrared Telescope

This mission, consisting of a single 8-to-12-m telescope operating in the far infrared, with a cold primary mirror, could serve as a building block for the Life Finder (described below) while carrying out a range of scientific programs beyond the capabilities of the Space Infrared Telescope Facility (SIRTF) and the JWST. These programs include probing the epoch of energetic star formation in the redshift range $l<z<10$ at a wavelength regime that can easily detect continuum and cooling line emission from dust enshrouded primeval galaxies with an angular resolution capable of isolating individual objects at or below the limits of the Hubble Deep Field; investigating the physical processes that control the collapse and fragmentation of molecular clouds to produce stars of various masses by mapping cold, dense cores at better than 100 AU resolution at the peak of their dust emission and using gas phase tracers such as H_2, H_2O, CO, OI, and NII; learning about the era of cometary bombardment that may have determined the early habitability of Earth by making high spatial resolution maps of the distribution of ices and minerals in the Kuiper Belts surrounding nearby stars; and studying the nature of the recently discovered objects in the Kuiper Belt of the solar system that may be characteristic remnants of the planet formation process. New technologies in focal planes, cryogenics, telescope primary mirrors (fabrication, test, packaging and deployment) and telescope structures will be needed.

To understand the early Universe, astronomers need to observe how energy, gas, and dust are created and how this energy, gas, and dust form stellar and planetary systems. Theory and recent space experiments indicate that observations of very cold, faint objects will provide information needed to develop answers to these questions. The peak intensity of this radiation is in the far-infrared and submillimeter regions of the spectrum. The implementation concept for this mission vision is to put into space a large, very cold telescope mirror to focus far-infrared and submillimeter radiation onto a special purpose large-area array and a very sensitive spectrometer. The telescope primary mirror would be large, in order to collect the very faintest radiation, and very cold to keep scattered and thermal emission of the mirror from blinding the very weak signal from space. Current estimates are that NASA will require a telescope aperture in excess of 10 m, actively cooled to less than 4 K with an optical surface figure error of 10 μm RMS. Technology to accomplish this mission needs development.

3.3 Optical and Ultraviolet Telescope

A successor to HST, operating at ultraviolet and optical wavelengths, this telescope could enable forefront science in all areas of modern astronomy. It would focus on the era from redshifts $0<z<3$ that occupies over 80% of cosmic time, beginning after the first galaxies, quasars, and stars emerged into their present form. Research to be conducted in the post-HST era will include studies of dark matter and baryons, the origin and evolution of the elements, and the major formation phase of galaxies and quasars. A large-aperture, optical-ultraviolet telescope in space would provide a major facility in the second quarter of the century for addressing scientific problems such as: Where is the rest of the unseen universe? What is the interplay of the dark and luminous universe? How did the intergalactic medium collapse to form galaxies and clusters? When were galaxies, clusters, and stellar populations assembled into their current form? What is the history of star formation and chemical evolution? Are massive black holes a natural part of most galaxies?

Technologies include telescope primary mirrors (fabrication, test, packaging and deployment), optical coatings, telescope structures, large-area focal planes, and devices for ultraviolet-sensing instruments.

3.4 Life Finder

A long-term goal is the detailed study of life and its evolution in ecosystems beyond the solar system. Achieving that goal will require observations beyond those possible with the TPF. For example, searching the atmospheres of distant planets for unambiguous tracers of life such as methane (in terrestrial concentrations) and nitrous oxide requires a spectral resolving power of about 1,000. The Life Finder would provide high-resolution spectroscopy on habitable planets identified by TPF. This information would extend the reach of biologists, geophysicists, and atmospheric chemists to ecosystems far beyond Earth.

The Life Finder telescope and instrument system will provide moderate resolution spectra of the atmosphere and surface of a planet in orbit about another star. The planet, itself will not be resolved, but rather evidence for the presence of life on the planet will be sought in the spectrum of the light reflected from the planet. Current research suggests that a 20-m clear-aperture space telescope functioning in the visible and infrared will be required to collect the extremely faint radiation and examine the radiation spectroscopically.

3.5 Far-Infrared and Submillimeter Interferometer

This space-based interferometer would be capable of detecting the far-infrared and submillimeter light from stars forming in the youngest galaxies. JWST will study the visible starlight from forming galaxies that has been red-shifted into the near infrared by the expansion of the universe. However, typically half, and sometimes more than 99% of the starlight of a galaxy is absorbed by dust in that galaxy and reradiated in the far infrared. This emission is red-shifted further into infrared or into the submillimeter bands. An interferometer consisting of three 15-to 25-m telescopes with a 1-km baseline would have the sensitivity and angular resolution (0.02 arcsec at a wavelength of 100 μm) needed to study the physical conditions in these young galaxies. In addition to cosmological studies, the interferometer would be able to observe collapsing protostars deeply embedded in their parental molecular clouds, providing valuable constraints on models for star formation.

3.6 Stellar Imager

The Stellar Imager (SI) will determine the long-term variability of the Sun by imaging other solar-like stars for the purpose of developing and testing a solar dynamo model with predictive capabilities. SI will image dozens of Sun-like, magnetically active stars with sufficient resolution to see the patterns of field emergence and evolution, revisiting stars frequently over up to a decade to map out the patterns in the dynamo, and to test and validate dynamo models. It will make use of astroseismic methods to image the internal rotation profiles of stars.

The nine mission visions described above require new technology in optics, instruments, sensors, and focal planes. The research and technology development is very compelling research.

4. INNOVATIVE TECHNOLOGIES

The origins program requires innovative technologies before we can meet our system requirements. Some of the systems we wish to establish in orbit and their requirements are

1. **A 4-to-10-m telescope with scattered light control in the optical and infrared coronagraph to one part in 10^9**
   1.1. Large high-precision optics
      - Requirements
         - < 25kg/m^2
         - < 7-nm RMS surface error at 4 to 100 cycles /aperture
         - 4-to-10-m diameter
      - Technologies
         - Mirror substrate materials
         - Optical figure processing
         - Surface metrology
         - Highly reflecting, low scatter coatings for white-light, amplitude, phase, polarization control

1.2. Image and pupil planes stops and masks
    - Requirements
        - Innovative optical designs to control internal scattered light
        - Masks of high dynamic range with precision amplitude and phase control to a part in 10^9
    - Technologies
        - Innovative optical designs
        - Optical material science
        - Nano-structure science and technology
        - Optical metrology and test methods

1.3. Wavefront sensing and control
    - Requirements
        - Sense and control the extended surface area to $\lambda/10^4$ at mid spatial frequencies for a flight-like system
    - Technologies
        - Innovative optical designs (interferometry)
        - Sources (lasers)
        - Calibration
        - Focal planes, on-board processing, algorithms
        - Actuators

1.4. High actuator-density deformable mirror
    - Requirements
        - Consistent with control of unwanted radiation to a part in 10^9.
    - Technologies
        - Innovative optical designs for active control of amplitude and phase
        - Micro- and nanolinear actuators processed into a very large scale integration
        - Algorithms
        - Materials science, microfracture, and fatigue

1.5. Stability of the point-spread function
    - Requirements
        - Stable for longest planned exposure times, temperature variation, repointing accelerations, etc.
        - Underdevelopment
    - Technologies
        - Innovative optical system engineering ideas
        - Validation of tools

1.6. End-to-end system test beds

2. A 30-m diameter diffraction-limited optical system
3. An observatory with angular resolution at optical wavelengths equivalent to a 500-m baseline
4. A 20-m cryogenically cooled (4 K) telescope system

5. CONCLUSION

The NASA Origins program is clearly the most ambitious program NASA has undertaken since the Apollo days. Venturing forth out side the solar system into the great depths of interstellar space to seek answers to two of the most profound and compelling questions man has ever asked:

Are we alone?

How did we get here?

is extremely exciting. The tools of this adventure, that is our "spacecraft" is a set of the most powerful optical systems ever built.

ACKNOWLEDGEMENTS

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

REFERENCES

1. Jet Propulsion Laboratory, 2002, *Origins 2003: Roadmap for the Office of Space Science (NASA)*, JPL 400-1060 10/02
2. http://SIRTF.caltech.edu/
3. http://ngst.gsfc.nasa.gov/
4. http://planetquest.jpl.nasa.gov/TPF/tpf_index.html
5. http://research.hq.nasa.gov/code_s/nra/current/nra-03-oss-01/appendA4_2.html